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TOPAZO 2.0 - A program for computing de-convoluted and realistic observables around the Z^0 peak

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Program classification: 11.1

The program `TOPAZO` is designed for computing Z^0 parameters, de-convoluted and QED-dressed cross sections and forward-backward asymmetries of e^+e^- annihilation into fermion pairs and of Bhabha scattering around the Z^0 peak, over both a completely inclusive experimental set-up and a realistic one, i.e. with cuts on acollinearity, energy or invariant mass and angular acceptance of the outgoing fermions. The new version, 2.0, offers the possibility of imposing different experimental cuts on cross sections and forward-backward asymmetries in a single run, and includes radiative corrections whose effect can become relevant in view of the present and foreseen experimental accuracy. Moreover, an additional option is included, which allows an estimate of the theoretical uncertainty due to unknown higher-order effects, both of electroweak and QCD origin. With respect to the version 1.0, the code is available in the form of `SUBROUTINE`, in order to render more viable the use of the program for aims not planned by the `TOPAZO` package itself.

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NEW VERSION SUMMARY

Title of new version: `TOPAZO` 2.0

Catalogue number:

Program obtainable from: CPC Program Library, Queen's University of Belfast, N. Ireland (see application form in this issue)

Reference to original program: `TOPAZO`; *Cat. no.:* ACNT; *Ref. in CPC:* 76 (1993) 328

Authors of original program: Guido Montagna, Oreste Nicrosini, Giampiero Passarino, Fulvio Piccinini and Roberto Pittau

The new version supersedes the original program

Licensing provisions: none

Computer for which the new version is designed: VAX, HP-APOLLO 7000; *Installation:* INFN, Sezione di Pavia, via A. Bassi 6, 27100 Pavia, and Sezione di Torino, via P. Giuria 1, 10125 Turin, Italy

Operating system under which the new version has been tested: VMS, UNIX

Programming language used in the new version: FORTRAN 77

Memory required to execute with typical data
300-600 kbyte as evaluator of observables in seven energy points

No. of bits in a word: 32

No. of processors used: 1

The code has not been vectorized

Subprograms used: NAGLIB [1]

No. of lines in distributed program, including test data, etc.: 12343

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Keywords: e^+e^- annihilation, Bhabha scattering, LEP, Z^0 resonance, electroweak, extrapolated and realistic experimental set-up, QCD corrections, QED corrections, pure weak corrections, radiative corrections, Minimal Standard Model, de-convoluted and realistic observables,

theoretical uncertainties.

Nature of physical problem
An accurate theoretical description of e^+e^- annihilation processes and of Bhabha scattering at the Z^0 resonance is necessary in order to compare theoretical cross sections and asymmetries with the experimental ones as measured by the LEP collaborations. In particular a *realistic* theoretical description, i.e. a description in which the effects of experimental cuts, such as maximum acollinearity, energy or invariant mass and angular acceptance of the outgoing fermions, are taken into account, allows the comparison of the Minimal Standard Model predictions with experimental *raw* data, i.e. data corrected for detector efficiency but not for acceptance. The program takes into account all the corrections, pure weak, QED and QCD, which allow for such a *realistic* theoretical description.

Method of solution
Same as in the original program. A detailed description of the theoretical formulation and of a sample of physical results obtained can be found in [2].

Reasons for the new version
The new version gives the possibility of computing observables in an experimental set-up with different cuts on cross sections and asymmetries, according to the most recently published LEP data. Radiative corrections whose effect can become relevant in view of the present and foreseen experimental accuracy have been included. An option is added which allows an estimate to be made of the theoretical uncertainty associated with unknown higher-order radiative corrections of electroweak and QCD origin.

Restrictions on the complexity of the problem
The theoretical formulation is specifically worked out for energies around the Z^0 peak. Analytic formulas have been developed for an experimental set-up with symmetrical angular acceptance. Moreover the angular acceptance of the scattered antifermion has been assumed to be larger than the one of the scattered fermion. The prediction for Bhabha scattering is understood to be for the large-angle regime.

Typical running time
Dependent on the required experimental set-up. As evaluator of observables in seven energy points, between 10 (extrapolated set-up) and 270 (realistic set-up) CPU seconds for HP-APOLLO 7000, corresponding to 100-2500 CPU seconds for VAX 6410. As estimator of the theoretical uncertainty, it requires about 5400 CPU seconds for HP-APOLLO 7000, for a single energy point.

Unusual features of the program

Subroutines from the library of mathematical subprograms NAGLIB for the numerical integrations are used in the program.

References
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LONG WRITE-UP

1 Introduction

The high precision reached by the four LEP experiments has motivated several groups in assembling Monte Carlo programs or semi-analytical codes for giving accurate theoretical predictions relevant in the region around the Z^0 peak [1-6]. As a consequence we have by now several electroweak libraries for radiative corrections at LEP energies. This is a very important fact because, when precision physics is the main goal, continuous cross-checks are needed, especially at the moment when several new effects have been computed, due for instance to QCD corrections or large-m_t behaviour [7].

As it stands `TOPAZ0` can be used to compute Z^0 parameters and deconvoluted observables but also to obtain predictions for QED-dressed distributions over a realistic set-up resembling the experimental *raw* data. The new version, `TOPAZ0` 2.0, offers improvements both in the direction of computing observables in a realistic set-up according to the selection criteria of the most recently published experimental data and in the direction of taking into account radiative corrections whose effect can become relevant in view of the experimental accuracy reached at present and foreseen for the near future. As far as the first kind of improvements is concerned, `TOPAZ0` 2.0 allows one to put different cuts on the cross section and the forward-backward asymmetry in a given channel, thus matching the set-up adopted by some of the LEP collaborations. As far as the second kind of improvements is concerned, all recently computed electroweak and QCD corrections are implemented. Moreover, further QED corrections whose size can become comparable with the foreseen experimental accuracy are included.

For the time being, a particularly important item is to estimate the uncertainty intrinsic to the theoretical predictions. For instance as a consequence of the high experimental accuracy reached by the LEP collaborations, the theoretical uncertainty affects the determination of the unknown parameters of the standard model [8]. To this aim, a new feature has been implemented in `TOPAZ0`, namely the possibility of running the evaluator over several theoretical options, related to different implementations of higher orders in the perturbative expansion. As a result, when choosing the proper branch in `TOPAZ0`, the code returns an estimate of the theoretical uncertainty of electroweak and QCD origin.

With respect to the previous version, the code has been rearranged in the form of `SUBROUTINE`, in order to render more viable the use of the program for

aims not planned by the TOPAZ0 package itself.

2 The most important new features

In the following we list and shortly comment the most important modifications of TOPAZ0. They can be classified into three classes.

TECHNICAL MODIFICATIONS

- The present version allows the experimental cuts on cross sections and asymmetries in a given leptonic channel to be treated separately, according to the most recently adopted experimental strategy. To this aim the routines OBSERVABLES and OBSCUT have been updated. For instance the present version allows the computation of an extrapolated cross section and a cut asymmetry in the same run.

- The new flag OTHERR has been included. For OTHERR = Y the evaluator runs over several (2^7) theoretical options, which reflect different (but not antithetic) implementations of radiative corrections, leading to a different treatment of missing higher-order terms. For OTHERR = Y the program returns a separate estimate of the weak and QCD uncertainty on the one hand and of the electromagnetic one on the other hand.

- The code has been prepared in the following form of SUBROUTINE:

  ```
  SUBROUTINE TOPAZ0(NRST,TRS,TZM,TTQM,THM,TALS)
  ```

  where
  NRST: the number of centre of mass energies
  TRS: the values of centre of mass energy (GeV)
  TZM: Z^0 mass (GeV)
  TTQM: top-quark mass (GeV)
  THM: Higgs boson mass (GeV)
  TALS: $\alpha_s(M_Z)$
  are the basic input parameters. Moreover, the SUBROUTINE TINPUT is provided in order to allow the user to supply the experimental cuts for a given Z^0 decay channel and to select among different theoretical options. The meaning of the latter input parameters/flags is summarized at the beginning of SUBROUTINE TINPUT. In particular, as input/output facility, the flag OMON allows to write down the results for the de-convoluted

and realistic observables (`OMON = Y`), or to store them into appropriate common blocks `/TTH, /TPO, /TPWTH` (`OMON = N`). This second choice is supplied for fitting purposes.

THEORETICAL IMPROVEMENTS:
PURE WEAK AND QCD CORRECTIONS

An important fact to realize is that there were several new calculations of radiative corrections in the last couple of years: their effect must be understood, classified descriptively, systematized and codified. Here it will only be possible to present a brief summary list of some of these effects:

- By using a dispersion relation the value of $\alpha(M_Z)$ obtained from experimental data is now $\alpha(M_Z) = (128.87 \pm 0.12)^{-1}$ [9].
- Two-loop heavy top effects in $\rho, g_{V,A}(b)$ for arbitrary values of m_H [10].
- $\mathcal{O}(\alpha\alpha_s)$ final state radiation [11].
- $\mathcal{O}(\alpha\alpha_s)$ corrections to vector boson self-energies [12].
- Complete $\mathcal{O}(\alpha_s^2 \frac{m_b^2}{M_Z^2})$ corrections to Γ_A, including NNLO terms for the running b-quark mass [13].
- Complete $\mathcal{O}(\alpha_s^2)$ corrections to Γ_Z and $\mathcal{O}(\alpha_s^3)$ corrections to Γ_h [13].
- $\mathcal{O}(\alpha_s G_F m_t^2)$ corrections to Γ_b, the FJRT effect [14].
- The $\mathcal{O}(\alpha\alpha_s^2)$ correction to ρ [15].

To illustrate the numerical relevance of those effects included in our electroweak library we can compare the peak cross sections and the forward-backward asymmetries for μ, τ and hadronic channels in a fully extrapolated set-up and for the same input parameters as used in [6] (see table 1).

Results	TOPAZ0	TOPAZ0 2.0
σ_μ	1.4912	1.4900
σ_τ	1.4836	1.4824
σ_{had}	30.615	30.591
$A_{FB}(\mu)$	0.0047	0.0039
$A_{FB}(\tau)$	0.0047	0.0039

Table 1: The effect of the new weak and QCD corrections implemented in TOPAZ0 2.0 for $E_{c.m.} = 91.222$ GeV, $M_Z = 91.175$ GeV, $m_t = 200$ GeV, $m_H = 250$ GeV and $\alpha_s = 0.125$

THEORETICAL IMPROVEMENTS: QED CORRECTIONS

- The exact $\mathcal{O}(\alpha)$ initial-final state interference (including hard bremsstrahlung) has been added for the leptonic channels as follows. The soft and virtual contribution has been included as a 1-dimensional spectrum ($d\sigma/d\cos\vartheta$, ϑ being the fermion scattering angle), taken from [16] and numerically integrated over the forward and backward hemispheres to build the correction to the cross section and the asymmetry. For the hard bremmstrahlung contribution, the 5-dimensional spectrum quoted in [17] has been worked out analytically to obtain a twofold distribution ($d\sigma/d\cos\vartheta dE_\gamma$, E_γ being the photon energy) and then numerically integrated as above. The analytical work performed on the hard photon part allows the computation of the interference correction with no substantial change in CPU time. The inclusion of the interference contribution is controlled, for each energy point, by a new flag `ONIF`. For `ONIF = Y`, the new subroutine `IFINT` is called and the correction to the cross section and the asymmetry is returned after calling `FUNSUBS` and `FUNSUBH` for the soft and hard contribution, respectively. It should be pointed out that the treatment of the intial-final state interference is exact for $s-$channel annihilation but approximate for full Bhabha scattering.

- The $\mathcal{O}(\alpha^2)$ leptonic and hadronic contribution from initial-state radiation according to [18] has been included as follows. The soft and virtual

contributions are computed using the analytical formula given in [18]. For the hard contribution, the 1-dimensional spectrum of [18] has been integrated numerically. The total relative contribution to the cross sections in the hadronic and leptonic channels is returned for each energy point (for `ONP = Y`) after a call to subroutine `PAIRS`, which in turn calls the subroutines `FUNSUBE`, `FUNSUBMU` and `FUNSUBHP`, for e, μ and h $\mathcal{O}(\alpha^2)$ hard contributions respectively.

References

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3 Test Run Output

The typical calculations that can be performed with the new version of the program are illustrated in the following example.

```
RESIDUAL WEAK CORRECTIONS ARE COMPUTED AT THE PEAK
PAIR PRODUCTION EFFECT IS INCLUDED FOR EACH ENERGY
I-F STATE INTERFERENCE IS INCLUDED FOR EACH ENERGY  FOR LEPTONS ONLY
S+T CHANNEL FOR ELECTRONS ARE COMPUTED
NO CUT ON THE REDUCED ENERGY IS ASSUMED
FULL PHASE SPACE FOR FINAL STATE EM RADIATION  IS ASSUMED

 MINIMUM ANGLE OF MU(-) (DEG):                          0.00000E+00
```

```
MINIMUM ANGLE OF MU(+) (DEG):                       0.00000E+00
MAX. ACOLLINEARITY ANGLE FOR MUONS (DEG):           0.18000E+03
MINIMUM ANGLE OF TAU(-) (DEG):                      0.00000E+00
MINIMUM ANGLE OF TAU(+) (DEG):                      0.00000E+00
MAX. ACOLLINEARITY ANGLE FOR TAUS (DEG):            0.18000E+03
ENERGY THRESHOLD  FOR ELECTRONS (GEV):              0.10000E+01
MINIMUM ANGLE OF E(-) (DEG):                        0.40000E+02
MINIMUM ANGLE OF E(+) (DEG):                        0.00000E+00
MAX. ACOLLINEARITY ANGLE FOR ELECTRONS (DEG):       0.25000E+02


CURRENT VALUES FOR THE PARAMETERS ARE:
Z MASS (GEV)     =  0.91189E+02       TOP MASS (GEV) =  0.17400E+03
HIGGS MASS (GEV) =  0.30000E+03       ALPHA_S        =  0.12400E+00

W MASS    (GEV)       =         0.802951E+02
NU                    =         0.167156E+00
ELECTRON              =         0.839136E-01
MUON                  =         0.839129E-01
TAU                   =         0.837222E-01
UP                    =         0.300439E+00
DOWN(STRANGE)         =         0.383139E+00
CHARM                 =         0.300387E+00
BOTTOM                =         0.376022E+00

SIN^2(E)              =         0.232208E+00
SIN^2(B)              =         0.233490E+00
A_FB(L) EFF.          =         0.150042E-01
A_LR EFF.             =         0.141608E+00
TOTAL WIDTH (GEV)     =         0.249613E+01
G_H/G_E               =         0.207727E+02
SIGMA0_H  (NB)        =         0.414425E+02
G(B)/G(HAD)           =         0.215718E+00
A_FB(B)               =         0.991510E-01
HADRONIC WIDTH (GEV)  =         0.174312E+01
A^POL_FB(B)           =         0.934252E+00
A_FB(C)               =         0.706791E-01
G(C)/G(HAD)           =         0.172328E+00
```

```
 DECONVOLUTED FB-ASYMMETRIES ARE:
Z-EXCHANGE ONLY

 ELECTRON             =        0.1500028E-01
 MUON                 =        0.1500028E-01
 TAU                  =        0.1497573E-01
 CHARM                =        0.7063442E-01
 BOTTOM               =        0.9875908E-01


 DECONVOLUTED FB-ASYMMETRIES ARE:
COMPLETE

 ELECTRON             =        0.1628186E-01
 MUON                 =        0.1628186E-01
 TAU                  =        0.1629466E-01
 CHARM                =        0.6814782E-01
 BOTTOM               =        0.9661819E-01



 OBSERVABLES ARE

 E_CM (GEV)            =          0.91300E+02

 SIGMA(E)   (NB)       =        0.1195475E+01 +/-        0.1745525E-03
 SIGMA(MU)  (NB)       =        0.1486515E+01 +/-        0.8608965E-04
 SIGMA(TAU) (NB)       =        0.1479019E+01 +/-        0.8288089E-04
 SIGMA(HAD) (NB)       =        0.3051606E+02
 A_FB(E)               =        0.1421349E+00 +/-        0.1666541E-03
 A_FB(MU)              =        0.7492082E-02 +/-        0.7530680E-05
 A_FB(TAU)             =        0.7519941E-02 +/-        0.7543220E-05
 A_FB(C)               =        0.6317556E-01
 A_FB(B)               =        0.9483699E-01
```